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Sheltering megalithic Temples in Malta – evaluating the process through data collection and modelling

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Abstract. Since their excavation, a number of the sites listed as part of "The Megalithic Temples of Malta" inscription on the UNESCO World Heritage list have been afflicted by material and structural problems, including collapses. Therefore, three of these sites, the Ħaġar Qim, Mnajdra and Tarxien Temples, were protected by open-sided shelters, to address some of the principal causes of deterioration (e.g. direct rainfall, surface weathering, thermal stress). Environmental monitoring, condition assessments and biological surveys of the three sites took place before and after sheltering and are still in progress. To understand how the shelters are affecting these structures, a research programme has started aimed at analysing, through Computational Fluid Dynamics (CFD), the environmental data collected over a period of more than ten years. The aim of using CFD on the Temples is to provide detailed information on how different environmental conditions can affect the sites. For the CFD, macro and meso scale approaches will be used. The macroscale model represents the regional environment, including the all-terrain features around the Temples. Mesoscale modelling represents the Temple structures in a more detailed way. The final goal is to find confident correlations between CFD, and representative areas selected within the Temples showing particular deterioration patterns. All this information will be integrated with the results of in situ analyses to identify the causes of material deterioration and possibly mitigate against them.

1. Introduction

1.1. Background and context

The megalithic Temples of Malta are free-standing stone structures which started being constructed around 3,500 B.C. and continued being used until 2,500 B.C [1] Six of these sites have been included on the UNESCO World Heritage List as 'The Megalithic Temples of Malta' inscription (16th session of the World Heritage Committee, 1992).

The structures are composed of an outer and inner limestone megalithic wall running alongside each other, with an infill made of smaller and larger stones, soil and other compacting material between these two. Evidence both within the remains excavated, and in the artefacts found within (including contemporaneous stone "models" [1]) show that these structures were roofed. This was done through the corbelling method, evidence of which still survives in these structures [2] (figure 1).

Figure 1. Corbelling found at Mnajdra South Temple, giving an indication of the original height of these structures

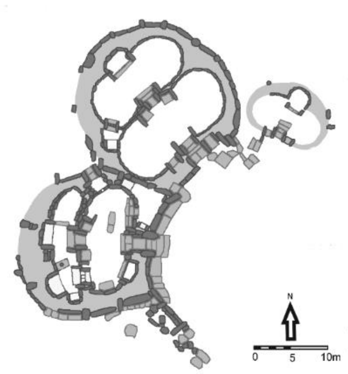

Figure 2. Typical inner layout of a Temple structure.

The typical layout of these complexes can be seen in figure 2, which shows the Mnajdra complex composed of three of these apsed structures. The Ħaġar Qim complex has two such structures; Tarxien, the largest of these complexes, has four of these apsed structures [3].

The Ħaġar Qim and Mnajdra complexes were covered by a protective shelter in 2008 and 2009 respectively, and this after much deliberation, with the aim of slowing the deterioration processes affecting the sites [4]. Subsequently the Tarxien Temples were also protected by means of a protective shelter in 2015. These protective shelters have already shown conservation-related benefits, with the elimination of periodic collapses of megaliths such as those which had occurred after heavy rain in Ħaġar Qim and Mnajdra [5-8], and periodic flooding of the Tarxien complex.

1.2. Objectives

The primary objective of this work is to outline a methodology, using Computational Fluid Dynamics (CFD), to guide research into conservation-related problems of archaeological and historical structures such as Malta's megalithic Temples. A data-driven multiscale approach is being used for the simulations where input data for boundary conditions are based on environmental monitoring carried out on site. The output from the modelling will provide possible correlations between the simulated environmental variables and problematic areas showing particular damage patterns, also highlighted from previous investigations, inside the Temples. These areas are being studied in detail through non-invasive portable instruments (e.g. XRD/XRF, FTIR, Raman); the results will eventually be fully integrated with the CFD information to try to elucidate the cause/effect relationship of identified deterioration forms and patterns. This part of the research will be the subject of a future paper.

1.3. Weathering processes

The main types of deterioration forms seen in the three Temple complexes are powdering, flaking, fissuring and alveolar weathering of the Globigerina Limestone megaliths [8] and the occasional presence of superficial layers of calcite recrystallisation on the original stone for the Coralline Limestone, as observed under Scanning Electron Microscope, by Mandrioli *et al.* [9]. At times severe deterioration of the megaliths, together with loss of infill and subsequent destabilisation due to heavy rains, led in the recent past to severe collapses in these three Temple sites. The main responsible factors and the consequent related weathering processes identified mainly before the installation of the shelters are highlighted in figure 3.

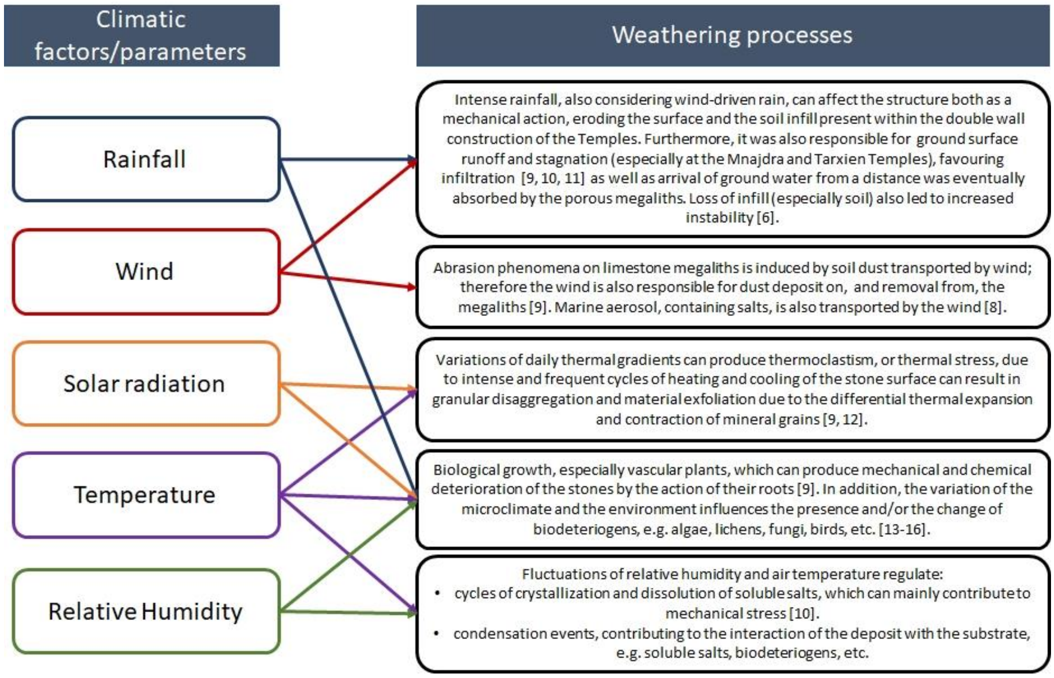

Figure 3. Climatic factors and related weathering processes identified mainly before the installation of the shelters at the Ħaġar Qim, Mnajdra and Tarxien Temples.

Nowadays, thanks to the action of the shelters, the main problems related to the direct and indirect action of rainfall and solar radiation are for the most part attenuated and/or even eliminated. Nevertheless, salt cycles are to be carefully monitored and investigated, as well as relative humidity and temperature fluctuations, in addition to wind action on the megalithic surfaces in the new microclimate/s created by the shelter. Also being studied are surface conditions, including in the stone and on the ground, inside and outside the Temples.

1.4. Landscape, topography and terrain

The Temples of Ħaġar Qim and Mnajdra are located on the southwest coast of Malta (figure 4). The landscape around them is largely garigue, interspersed with terraced fields, many of which have been abandoned. The predominant wind is North Westerly (NW) [17]. These two Temples are located near the coastline formed predominantly of steep cliffs created by the Maghlaq Fault. The Mnajdra complex is built in a hollow on the Lower Coralline Limestone slopes around 85 meters above sea level and around 200 meters from the sea, while Ħaġar Qim is built on the crest of a Lower Globigerina Limestone ridge around 600 meters from the sea, at an elevation of around 130 meters above sea level [18]. The region between the coastline and Temples is again largely garigue, partly covered by a relict agricultural landscape. The complex configuration of the coastline, and the steep cliffs that characterise it, cause wind flow from the direction of the sea to become highly asymmetric and turbulent. Small changes in the main wind direction or magnitude may have a significant influence near and within the Temples.

Figure 4. Plan showing the locations of the three sites under study on the island of Malta. (Adapted from the INSPIRE geoportal from a dataset compiled by the Environment & Resource Authority, Malta).

2. State of the art

2.1. Fluid simulations in heritage science

The majority of papers that describe fluid dynamic simulations in cultural heritage are related to air movement and the resulting ventilation of spaces (90% of the papers reviewed in [19]), most of which indoors (70%). There is a varying level of complexity of the CFD approach applied to heritage [20, 21, 22]. In the simplest of cases, simulations aim at obtaining a visualisation of airflow in a given environment. Other, more elaborate, simulations provide supporting evidence for the historical interpretation of a site [23, 24]. Finally, simulations intended as an integral step within a design process, a conservation project or, more generally, to support decision-making, can also be found [25, 26, 27].

The processes of change which are of interest to researches of heritage environments take place generally over decades or years rather than hours or seconds. Short-term processes such as relative humidity or temperature fluctuations are usually a concern because of their long-term effects. The emphasis on long-term material change and the cumulative effects of rapid variations can be seen to be at odds with the nature of CFD, which is best suited for the simulation of short time-spans or steady-state problems.

There are 3 main ways of Time representation in CFD. First, the simulation can represent an unchanging state that is true for a certain period that could be infinitely long, which is known as steady-state. Secondly, pseudo-transient simulations can be taken into consideration, which represent a series of steady-state scenarios that approximate a continuous variation, for example, winter and summer conditions or monthly conditions. In other words, these are time steps that are significantly longer than the time that the system takes to reach steady-state conditions. Finally, there are transient simulations, which aim to resolve equations for every time step of the evolution of the system.

As stated in the [19] only a quarter of the published simulations are experimentally validated. There is a need for more comparisons between simulations and real-world data, collected in the simulated environment. The difficulties of this task in heritage environments are many: slow change, the difficulty of monitoring, the uniqueness of the sites studied and their conditions. Since CFD aims at simulating the spatial distribution of a quantity, validations should also use spatially distributed data. There is a need for the development of benchmark cases that can be used for the validation of models for a diversity of conservation issues, to be used when other types of validation are not possible. Velocities indoors are usually low (under 0.1 m/s) and sometimes air flows may not be fully turbulent. Models employing modified versions of the $k - \varepsilon$ model, such as the Renormalisation Group (RNG) model, seem to provide acceptable results [28], but there needs to be a critical reflection on the use of turbulence models in indoor heritage spaces. There are references to the adoption of SST (shear stress transport) k-ω models for application in indoor environments [29]. Further research is needed in the assessment of the levels of turbulence found indoors and the methods to model it. Despite on the interaction between air and heritage materials, few published simulations include estimations of wall fluxes, such as evaporation or condensation of moisture or dust and gas deposition. This may be a valid assumption in many instances but should be explicitly discussed. The implementation of near wall modelling is arguably the most problematic area in turbulence modelling. Dealing with near wall modelling means focusing on the turbulent boundary-layer, such models will, additionally, require computational refinements close to surfaces that may differentiate heritage CFD models from other indoor simulations.

2.2. Fluid simulation in Urban Environment – guidelines

There have been several previous initiatives to establish best practice guidelines in the field of flow simulation in general and for application to the built environment.
As stated in [30], for general CFD applications the European Research Community on Flow, Turbulence and Combustion (ERCOFTAC) Best Practice Guidelines [31] is still the most comprehensive document. Special problems of micro-scale meteorological applications are however deliberately not addressed. Best practice guidelines on CFD for wind engineering problems have been published by the Thematic Network for Quality and Trust in the Industrial Application of CFD (QNET-CFD) [32, 33]. Besides these European activities, the Architectural Institute of Japan has conducted a cooperative project for CFD prediction of the pedestrian wind environment [34]. For the same application, a working group of the European COST action C14 "Impact of Wind and Storms on City Life and Built Environment" has compiled recommendations for conducting CFD simulations from a comprehensive literature review [35]. The closely related guideline of the VDI (the German Association of Engineers) concentrates on evaluation and validation of these models for flow around buildings and obstacles [36]. The guideline is structured according to the general steps of conducting a numerical simulation [31]. The main objective of the COST Action 732 [38] is the improvement and quality assurance of microscale obstacle-accommodating meteorological models and their application to the prediction of flow and transport processes in urban or industrial environments. This guideline focuses on applications of the statistically steady Reynolds-averaged Navier–Stokes (RANS) equations for situations with neutral stratification without dispersion modelling. However, users of other models like unsteady RANS (URANS) and Large eddy simulation (LES) models should consider the same suggestions. Differences and some more – but not extensive – information for URANS and LES applications are also given. The guideline provides general advice that should be considered when performing simulations for model validation and has been tested within the COST Action 732 [37].

Thus, this guideline should be addressed as the main guideline for development of best practice in the simulation of flows in heritage, by placing great attention on how to choose the target variables, approximate equations describing the physics of the flow, the geometrical representation of obstacles, computational domain, boundary conditions, initial data, computational grid, numerical approximations, time step size, iterative convergence criteria and other related variables.

2.3. Fluid simulation on Complex Terrains

There are studies which address turbulence modelling issues related to the simulation of flow over complex terrains using a coupling between NWP (Numerical Weather Prediction) code and a classical CFD (computational fluid dynamics) code [38].

In the field of geophysical fluid dynamics, numerical and laboratory scale modelling of atmospheric flows are the mainly investigated topics covering many different applications ranging from the determination of near-surface winds for wind energy applications to high-altitude atmospheric physics applications [39].

3. Problem definition

The first simulations in the current research project were produced for the Mnajdra Temples, in order to have a first representative case study. As already stated, these Temples are 85 meters above sea level and around 180 meters from the nearest coastline. This makes this site quite challenging from a fluid dynamics perspective. A slight change in wind speed or direction could completely change wind flow patterns in and over the Temple. Therefore, this site was chosen as the first site to be modelled. The site has also one of the simplest layouts of the entire group of Maltese Temples, which would help in the actual modelling itself.

In order to get representative velocity vectors distribution inside what is still a complex Temple geometry, a high-resolution grid must be used. As the Temples are located near the coastline and on the cliff, this makes this case very sensitive and computationally expensive to get detailed velocity vectors inside sheltered and unsheltered Temple cases. Therefore, a different simulation approach is being proposed.

4. CFD approach

In this study, a multiscale flow domain process is being used. Three flow domains are identified; (i) the macro scale, (ii) the mesoscale, (iii) the microscale. In the macroscale domain, the characteristic length scale being model is of the order of the site dimensions, a few kilometres. Within the mesoscale domain, the geometry of the Temples is modelled in more detail. The characteristic length scales modelled in this case are of the order of the Temple principal dimensions, a few meters. Finally, in the microscale, the length scale modelled will probably be of the order of the boundary layer dimensions found over the rough stone surfaces, being a few millimetres.

In Stage 1 (macro-scale) verification and validation of pseudo-transient simulation will be performed - representing seasonal / monthly/ or day-night cycle, of wind speed, and direction. These simulation results will provide additional information such as a valid representation of boundaries (wind speed, temperature, turbulent kinetic energy dissipation rate of turbulent kinetic energy and turbulent intensity) which will be used as an initial condition for the mesoscale. In Stage 2 (mesoscale) verification and validation of pseudo-transient or transient simulation will be performed - representing averaged season (or month, or day-night cycle) conditions. In this stage, more accurate and detailed information about local wind flow magnitude and direction inside the Temples is obtained. By integrating additional environmental data (temperature, humidity, solar radiation, etc.) more realistic representations of the microclimate inside the Temple will be achieved. These simulation results will provide more representative time scale (seasonal/monthly/daily) data which will be used for correlation with the experimental data of *in situ* analyses using portable instruments, which is being planned. The aim of Stage 2 is to provide valid answers to what are the main causes of specific deterioration issues inside the Temple. Coupling methodology (macro and meso) will be tested, verified and validated. In Stage 3 (micro-scale) – the aim of micro-scale stage is the study of processes near the wall. (mass and energy transfer between solid surfaces and surrounding environment).

4.1. Verification and validation

Every multiscale flow domain stage (macro, meso and micro) must be verified and validated independently. The examination of the spatial convergence of a simulation is a straight-forward method for determining the ordered discretization error in a CFD simulation. The method involves performing the simulation on two or more successively finer grids. The term “grid convergence study” is equivalent to the commonly used term “grid refinement study”. Establishing grid convergence is a necessity in any numerical study. It is essential to verify that the equations are being solved correctly and that the solution is not sensitive to the grid resolution. The “grid convergence index” [40] is a standardized way to report grid convergence quality. It is calculated at refinement steps.

The proposed approach must also be validated. This will be done using 2D and 3D ultrasonic flow anemometers on site. Inlet profile validation will also be carried out. Vertical distribution of 2D ultrasonic anemometers used outside the shelter representing the main inlet boundary for mesoscale. An internal probe inside the Temple will include a 3D ultrasonic anemometer inside one the apses of e the

Temple. Global validation will be achieved by using installed environmental monitoring stations acquiring data, located outside the Temples.

The aim of verification and validation is the assessment of accuracy and reliability for computational simulations, which leads to a closer representation of Real word.

5. Conclusions

The aim of this paper is to propose a multiscale domain approach of CFD studies on cultural heritage (archaeological) sites by integrating different domain scales (macro, meso and micro). Thus, being a similar approach to coupling NWP (numerical weather prediction) with CFD code, this approach could provide a more detailed and more accurate microclimate simulation of the inside of these Temples. These results can then be used to find confident correlations between CFD and representative areas selected within the Temples showing deterioration patterns. These correlations will provide a deeper insight of the effects of shelters on the megaliths themselves and could also lead to the development of further mitigation measures against the deterioration of these sites.

Further studies must be carried out on specific coupling mechanisms between different domains for the integration of guidelines for the CFD simulation of flows in the urban environment. It is in fact planned that these simulations will also be carried out for the other sheltered, more complex sites of Ħaġar Qim and Tarxien. If proved to effectively represent the conditions in these very complex structures, this methodology could then possibly be used for the development of best practice guidelines in the simulation of flows in heritage structures.

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